



Report on Evaporation

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Report on Evaporation

A 'state of the art' report prepared by S. Dyck on behalf of the Committee on Evaporation, and presented at the General Assembly of the Association, Moscow, August 1971

GENERAL

Evaporation is one of the main components of the water budget. Although some headway has been made in the estimation of evaporation, the present state of development is unsatisfactory. There is a need for more theoretical and experimental studies, especially for application of the theory of turbulent diffusion to the realities of evaporation from cropped or forested surfaces. The dependence of evaporation on soil and vegetation factors is inadequately defined. The sensitive methods of measurement that have been developed still have considerable drawbacks. There is the problem that the high accuracy obtained at the measuring point is lost in the transfer of the measured values to larger regions. Above all, hydrology requires values of evaporation for whole catchments for use in water balance models. Hydrological data from remote areas are lacking for establishing global, continental and regional water balance models.

The importance of the study of evaporation is steadily increasing with the growing intensity of water resources management. To supply water for irrigation, industry and canals, demands increasing expenditure. Water for irrigation, which is brought to the fields at high cost must be used in the most economical way. The increasing use of large-scale nuclear power plants has caused a considerable heating of river water, resulting in higher evaporation rates. This makes it important to define the physical background to thermal pollution and such features as the temperature die-away pattern in a river.

In recent years there has been an increasing interest in evaporation studies. This paper presents a condensed review of evaporation assessment in the water balance. Other reports summarizing the state of knowledge in the same field are listed.

THE WATER BALANCE METHOD

Evaporation or evapotranspiration can be calculated from the general water balance equation, if all the other factors are given. The same principle can be applied in large scale or catchment studies and in small scale investigations using pans and lysimeters.

When evaporation is calculated as the residual item in a water balance, such as for the determination of lake evaporation, lake inflow and outflow must be measured; however, there is only a small number of lakes where such measurements are made.

For river basins reliable results can be expected only if the surface and groundwater flows can be adequately estimated and long period means are considered. It is the determination of changes in soil-water and groundwater storage and in deep percolation which presents the main difficulty in the estimation of evapotranspiration from river basins when the water balance method is used for shorter periods. This difficulty is being overcome by the continuous improvement of measurement techniques and by the development and application of the theory of water movement in the unsaturated and saturated zones. Representative and experimental basin studies can provide better estimates of evapotranspiration from the water balance, especially if energy budget studies are carried out at the same time.

Pan Evaporimeters

There are many different types of pan and tank evaporimeters in use. As standardization and proper exposure are two important factors for the application of pan data, WMO, through its Commission for Instruments and Methods of Observation, set up a Working Group to examine evaporation measurement. The Group concludes that pans are useful devices provided that the various observations can be reduced to a standard datum (CIMO—V/Doc. 60, 27. VII. 1969; Hounam, 1970).

Pan evaporation values can be used for estimating the evaporation from a free water surface, both for existing and planned storages. The value of pan network observations is increased if they are supplemented by standard climatological observations. Pan data corrected for vapour pressure gradients over the pan and the lake can provide useful information for lake evaporation estimation (Subbotin, 1964; Webb, 1966). Pan evaporimeters can serve as the basis for estimating evapotranspiration only for field capacity conditions; they are useless for drying soil conditions.

Lysimeters

Weighable lysimeters are the most common devices for obtaining actual evapotranspiration values at a point; such values can be used to check evapotranspiration estimated by empirical formulae. In spite of the drawbacks of these devices, due, in the main, to their limited dimensions, new lysimeter systems are under construction all over the world. WMO Tech. Note No. 83

(1966) gives a comprehensive survey of various lysimeters in current use. The field of application for this method will be further extended by increasing simplification, specialization and refinement of the lysimeter technique.

The effective use of the lysimeters is limited to types of vegetation which can be simulated within the container. Lysimeter use is impracticable in an arid environment with sparse, irregular and deep rooted vegetation and also in the great forests of the temperate humid zones (Hounam 1970). Non weighing lysimeters may be of either the constant water table or percolating types. The main task of the so-called drainage lysimeter is the estimation of natural groundwater recharge. Useful estimates of evapotranspiration can be obtained from these relatively inexpensive instruments by measuring soil moisture through the depth of the soil profile and evaluating the change in water content.

THE ENERGY BUDGET METHOD

The energy budget method was first applied by Schmidt (1915) for determining the evaporation from oceans. The method has been employed subsequently by a number of workers, including Budyko (1956) who determined the evaporation from the land and water surfaces of the whole globe by this method.

The difficulty of measuring directly the sensible heat flux is as great as that of measuring the latent heat flux, however the ratio of the two fluxes was shown to be proportional to the ratio of the difference in temperature to that of vapour pressure (Bowen, 1926). By rearranging the energy balance equation and using the Bowen ratio the evaporation can be determined. Two assumptions implicit in the use of the Bowen ratio are: identity of the eddy transfer coefficients and constancy or similar variation with height of the sensible heat flux and the latent heat flux from the surface to the upper measuring point.

Carefully instrumented, the Bowen method is a very sensitive method for determining the actual evapotranspiration from different soil covers (Pruitt and Lourence, 1966; Fritschen, 1965; Tanner, 1960). Costly instrumentation is necessary for measuring the net radiation of the evaporating surface, the heat flux between surface and body (soil, water), and the vertical gradient of potential temperature and vapour pressure. Moreover, the identity of the transfer coefficients applies to the range of the laminar boundary layer at the contact face between the evaporating surface and the atmosphere. Within the range of the overlying turbulent layer, however, the eddy transfer coefficients for heat and water vapour may differ from one another according to the stability of the atmosphere (Pasquill, 1949; Rider, 1954b). The determination of the values of the transfer coefficients for a non-adiabatic condition is now of great importance in the determination of the die-away of river water heating by cooling water from power stations.

The considerable effort demanded by this method in measurement and analysis can be reduced by using sensitive net radiometers, high-capacity digital recording apparatus and automatic data processing. Applied by mobile energy budget stations, this method makes it possible to investigate the evapotranspiration of characteristic hydrological areas and to obtain regional values for short time intervals. The method is usually reliable for periods of less than a day and under optimum conditions for time periods of as small as one hour (Bertz, 1969).

The energy budget method compared favourably with the water balance method in tests carried out by Anderson (1954) at Lake Hefner, by Harbeck *et al.* (1959), Mchitarjan (1970), Timofeev (1963), Braslavskij and Vikulina (1954), Braslavskij and Sergina (1965), and by Kirillova (1970).

In the case of deeper lakes, computations are complicated by the need to take heat storage into account in addition to the advection of heat by inflow and outflow.

Initially the energy balance method was applied to determine evapotranspiration from low crops on wet locations. Recently good results have been obtained for different types of vegetation (Tajchman, 1967) and also for uniform forests (Rauner, 1960, 1965; Fedorov, 1964; Lutzke, 1966).

In conclusion, the energy budget method is fundamentally sound. More precise results await the theoretical determination of the relation between diffusivities for water vapour and heat under non-adiabatic conditions, and the improvement of instrumentation.

VAPOUR TRANSFER METHODS

These methods are all based on Dalton's eighteenth century work on evaporation.

Empirical Formulae

A number of different relationships have been derived using various combinations of measurements of surface temperature, vapour pressure, wind speed and vapour pressure deficit. Such relationships, for example, those of Konstantinov (1968) and Levenko (1969) have been employed for the assessment of evapotranspiration over catchment areas and plots.

Bulk Aerodynamic Method

This method has had a wide application in the estimation of lake evaporation. In general, evaporation is taken as being proportional to the product of windspeed and the humidity gradient. The method is discussed in WMO Techn. Note No. 83. Studies made in several countries show that this is the most reliable practical method for assessing lake evaporation at the present time.

The bulk aerodynamic method is difficult to apply to vegetation because the vapour pressure at the transpiring surface is rarely known and would also vary with time and space (Hounam, 1970).

Transfer Coefficient

While the bulk aerodynamic method relies on empirical constants, this method considers the measured values of the turbulent transfer coefficient. By analogy with molecular and other well-known transfer processes, Thornthwaite and Holzman (1939) derived an equation for the determination of the vertical vapour transport under simplified conditions. In order to calculate evapotranspiration, Rider (1954b) supplemented this formula by a term for zero-plane displacement. The main difficulty in determining evaporation from the vapour flux concerns the derivation of the transfer coefficient from the wind profile. The logarithmic wind function is valid only under neutral atmospheric conditions. Under non-neutral atmospheric conditions, which are very often periods of intensive evaporation, modified wind functions or suitable correction factors and measurement techniques must be used.

The error in calculating evaporation by means of the logarithmic wind function under non-neutral atmospheric conditions becomes smaller if the measurements are made close to the evaporating surface. Especially with root and tuber crops, however, which do not completely cover the soil zero-level, difficulties and larger sampling variations occur. The error introduced by the use of the logarithmic function can be up to at least 15 per cent of the calculated evapotranspiration.

One source of error in this method is due to the fact that aside from the turbulent mixture, thermal convection occurs during day time. This means that too low an evaporation is obtained, unless the share of convection is taken into account according to the techniques of Lettau (1949), Priestley (1959), or Monin and Obuchov (1951). This can also be effected by a variable factor of the transfer coefficient which is dependent on the stratification of temperature. A detailed description and further development of the method is given by Tajchman (1967), Monin and Jaglon (1965), Webb (1966), and Zilitinkevich (1970).

Covariance Method (Eddy Flux)

This is the most direct and most accurate method for determining evaporation from any surface. The direct measurement of the vertical water vapour flux passing a horizontal reference level was first mentioned by Swinbank (1951) and later described in more detail by McIlroy (1968) and by Dyer and Maher (1965). This method requires simultaneous measurements of the density of the air, the vertical component of wind speed, and the specific humidity of the air at only one height above the soil cover. The sensors (vertical anemometer and psychrometer) must operate with very low inertia. High demands are made on the sensitivity and efficiency of the devices for measurement and analysis. So far no devices are available which meet all the requirements of practical application. This method, however, is promising and its further development is desirable.

THE COMBINED AERODYNAMIC AND ENERGY BUDGET METHOD

Although the method of vertical vapour transport and the energy budget method are physically founded, they have disadvantages in their practical application in agricultural and hydrological studies. Considerable effort has to be devoted to measurement and evaluation and there is also the necessity of having to make the measurements over short time intervals. Furthermore, the measured values are only valid for the point of measurement. In estimating the water balance for catchment areas with a variety of soils and vegetation, much effort is necessary. Moreover, both methods provide the actual evapotranspiration without reference to the maximum that is possible and to the effect of soil moisture conditions and plant development on transpiration. A knowledge of these factors, however, is indispensable for practice in irrigation and in hydrology. Penman (1948) combined both the aerodynamic method and the energy budget method in a formula for the calculation of potential evaporation using standard meteorological data. In order to determine potential transpiration (evapotranspiration) he later introduced a stomatal and daylength factor designed to account for the effect of stomatal closure upon transpiration (Penman and Schofield, 1951). This formula was generalized by Monteith (1965). Its practical application, however, has been restricted so far since it is difficult to obtain representative values for the aerodynamic diffusion resistance and the surface diffusion resistance. The mean aerodynamic resistance can be calculated from wind speed and surface roughness with reference to crop height, Szeicz *et al.* (1969). The surface diffusion resistance may be calculated by means of the above-mentioned analytical techniques. The profile and residual method is suited to investigating short-term reactions whereas the energy balance method is preferred for long-term or large-scale catchment area studies (Szeicz and Long, 1969).

The advantage of the combined methods is that the simple parameters occurring can be measured or reliably estimated while the accuracy of the results is sufficient for many practical purposes. In order to provide the meteorological data for the various soil covers and soil types, which are necessary to apply the combined method for determining evapotranspiration, measurements of the different factors must be made under varying conditions.

The following investigations are necessary:

1. The systematic collection of data for relating surface roughness and plant growth for different crops. This also applies to the determination of the relationship between wind speed and surface roughness.
2. The investigation of the effect of a partial soil cover on evapotranspiration. This applies particularly to the early growth stages of crops.
3. The determination of the surface diffusion resistance for various crops by means of meteorological methods.

When evaporation from the surface of a region is limited by the availability of moisture, the resultant changes in the temperature and humidity of the air passing over the region are

reflected in the potential evaporation. Such interactions between regional and potential evaporation were taken into account by Bouchet (1963), who showed that changes in regional and potential evaporation, due to changes in regional moisture supply, are complementary. This concept of interaction has been formulated into a model by Morton (1970) in which the potential evaporation is estimated from regional climatological observations using modifications of the combination method. With such a climatological relationship, the regional evaporation, a product of complex climatic, soil moisture and vegetative processes, may be estimated by its effects on climatological observations (Morton, 1971).

EMPIRICAL FORMULAE FOR ESTIMATING EVAPOTRANSPIRATION

Simple equations based on the data usually observed at climatological stations are often employed for assessing evapotranspiration using evaporation values obtained from lysimeters by the energy budget method, or by using the aerodynamic profile method, empirical formulae for estimating 5-day, 10-day or monthly values of evapotranspiration have been developed which require measurements of only a few factors. These simple methods could be improved by evaluating the influence of the vegetation and its state of growth on evapotranspiration; data should be obtained for the most important vegetation types and soil classes by intensive lysimeter measurements.

A rough estimate of the annual distribution of evaporation is sufficient for some practical tasks—the determination of the natural recharge of groundwater for example. Using an approximation to the seasonal pattern, the annual values of evaporation can be divided into monthly values, and the monthly values into daily values. The annual distribution of evaporation is, of course, strongly influenced by the climatological conditions prevailing in a region. Under the same climatic conditions, it is dependent on the type of vegetation, the soil conditions and several other factors. The annual distribution of evaporation values from selected areas (arable crops, grass cover, etc.) can be derived from lysimeter results and other methods. For the approximate determination of annual values of actual evapotranspiration several useful methods have been developed employing the primary factors which influence evapotranspiration, e.g., available energy and precipitation, soil conditions and vegetation (Oldekop, 1911; Budyko, 1948, 1956; Bagrov, 1953; Kortum, 1961, 1968; Mezenцев, 1963; Talalaevskij, 1966; Demianczuk; 1967).

MAIN FIELDS FOR FUTURE RESEARCH AND STUDY

Improvements in measuring and estimating evaporation await developments along the following lines:

- (a) The improvement of the theory of evaporation, especially the theory of turbulent diffusion. There is a need for more theoretical and experimental studies of evaporation, especially for the theoretical determination of the relation between the diffusivities for water vapour and heat under non-adiabatic conditions.
- (b) The development of suitable operational instruments for measuring evaporation directly as an atmospheric flux over any natural surface. These instruments could be used in local research studies and in the calibration of other more robust but less accurate devices. They might also be used to determine the associations between the various diffusivities and in relating those associations to parameters easily measured continuously in the field.
- (c) The improvement of the theoretical foundations for modelling the natural evaporative process as a whole. To arrive at a better adaptation of the estimation of evapotranspiration to the quality of the soil, to soil moisture conditions, to the quality of the vegetation, etc., models for the transpiration flux at selected levels of the system soil–plant–atmosphere also need to be improved.

- (d) Assessment of evaporation over an area. The evapotranspiration amounts measured by lysimeters or by the energy budget method apply only to the location where the measurements have been taken; they are not directly transferable to larger heterogeneous areas. In order to determine the evapotranspiration of complex catchment areas for short-time intervals, these areas have to be sub-divided on the basis of morphological, pedological, hydrogeological, and plant physiological boundaries into areas of similar hydrological behaviour. These homogeneous units should then be calibrated by means of evaporation values representative of the respective locations, which have been determined by lysimeters, mobile energy budget stations, and other methods. It depends on the specific purpose of the investigation, on the accuracy required, and on the economic expenditure justifiable, how detailed the sub-divisions of a river basin and the measurement network must be. Changes in surface wetness are detectable through photographic methods. Since estimates of variations in soil moisture represent integrated values over areas they should lead to better estimates of areal evapotranspiration.
- (e) The development of methods for the quantitative assessment of the representativeness of point measurements of evapotranspiration.
- (f) Estimation of the effects of man-caused changes in evaporation. (Irrigation and drainage, man-made lakes, urbanization, evaporation control by chemical films and solid barriers, sealing of the soil, air pollution, modifications to water resources, agricultural and forest management, thermal pollution, etc.)

In general, a higher intensity of water resources management and use causes higher losses by evaporation. Thus, improvement of the estimation of evaporation and evapotranspiration is of growing importance for the planning of water resources systems, particularly when evaporation values are required for ever shorter periods. The most developed water balance models are based on daily values of evaporation and these are making increasing demands on the precision of the techniques for the measurement and calculation of evaporation.

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